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Vision of total renewable electricity scenario

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ABSTRACT

This paper analyses the reality of total renewable electricity scenario (TRES) from renewable energy sources (RES) as a totally green strategy of electric energy production. The paper is based on the EREC's Agency forecast until the year 2040, which foresees the share of 82% of RES, extended to 100% of RES. The key element that creates conditions for achieving this ambitious scenario is an innovative combination of RES and pump storage hydroelectric (PSH) power plants, the so-called Concept-H, which can simultaneously use the energy of local RES (sun and wind) and local precipitation (natural waterflows) and in this way can provide continuous supply of electric power and energy to consumers. The methodology is based on the model of equivalent RES and equivalent reservoir that allows a comprehensive view of available RES and hydro system. The total required land use of RES system would be 29,517 km^2 of RES (which would amount to about 0.5% of the total technical potential of using RES), total reservoir volumes would be 880 km^3 (which is only 8% of all artificial reservoirs built in the world to the date) and the orientation estimate of investment in TRES would then be approximately 1% of world GDP in 2009, which clearly shows that the TRES is realistically feasible. It has been shown that implementation of the green strategy of energy balance fulfilling can be realized with present day technology. Precisely this fact shows that further increase of efficiency of RES and their combining into RES–PSH power plants, along with increase in the cost of classic power fuels and the growing needs for environment protection, the proposed solution of TRES realization could be widely important and thus become a serious alternative to the existing energy strategies and a guideline to decision makers throughout the world.

Contents

Abbreviations: B, biomass; CF, capacity factor; Concept-H, RES + PSH power unit as the main building element of the future SEPS; EES, electric energy storage; EPS, electric power system; GT, geothermal; HE, hydroelectric; IPCC, Intergovernmental Panel on Climate Change; LHE, large hydro; M, marine; NRES, non-renewable energy sources; PSH, pump storage hydro; PV, photovoltaic; ORES, other renewable energy sources (HE + LHE + B + GT + M); RES, renewable energy sources; RES-C, renewable energy sources which can provide continuous supply to consumers; RES-I, renewable energy sources with intermittent energy production; SEPS, sustainable electric power system; smHE, small hydro; ST, solar thermal; TOTAL, total energy production; TRES, total renewable energy scenario/system; W, wind.

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Nomenclature

List of symbols

a, b, c, d	constants
CF	capacity factor of certain RES
E_{EPS}	energy required for sustainable EPS (SEPS)
E_{PSH}	energy produced from PSH
$E_{RES\text{-}C}$	energy produced from RES-C
$E_{RES\text{-}I}$	energy produced from RES-I
$E_{el(PV)}$	electric energy which the PV generator could produce
$E_{el(ST)}$	electric energy which the ST generator could produce
$E_{el(W)}$	electric energy which the W generator could produce
$E_{evap,t}$	evaporated volume from the equivalent reservoir over time period t
$E_{hyb,t}$	total equivalent reservoir stored energy in time period t
$E_{loss,t}$	energy losses from the equivalent reservoir over time period t
$E_{nat,t}$	total natural potential energy inflow over time period t
$E_{NRES(k)}$	energy of each fuel
$E_{prod_{MAX,t}}$	maximum energy production of upper reservoir of PSH in period t
$E_{prod,t}$	decision variable or the total energy outflow over time period t
E_{RES}	energy produced by RES power plant
$E_{RES,t}$	total energy inflow over time period t generated (pumped) by energy from RES
E_{TRES}	energy for TRES
EV	water from reservoir consumed by evaporation
$Ev_{i,t}$	monthly evaporation loss from reservoir i for time period t
g	gravity constant
H_{DIF}	difference between bottom level of upper storage and upper level of lower storage
H_n	net available drop
H_{nPS}	net head of pump station
H_{TE}	total head
H_U	upper water levels
$i\ (\zeta_i)$	mean productivity of a single reservoir that corresponds to the average value over the entire planning horizon
k	number of downstream reservoirs from reservoir i (plus itself)
f	type of fuel (coal, oil and natural gas)
m	number of reservoir
$M_{CO_2(Eq)}$	equivalent (weighed moving) value of CO_2 emission
$M_{CO_2(f)}$	unit emission of CO_2 from various fuels (coal, oil and natural gas)
N	number of fuels whose emission is being observed
n	number of time steps in the year
P_{el}	power of RES power plant
P^*_{el}	optimal power of RES
p_{RES}	equivalent value of RES-I power reference value
QC	consumptive use water discharges
Q_{nat}	natural water inflow discharge
Q_{RES}	artificial-RES water inflow discharge
R	total precipitation coming into the upper reservoir
R_E	reliability of the system by energy
R_V	reliability of the system by volume
Surface_i	mean surface area of i reservoir
t	time step-period
T_a	air temperature
v	wind velocity
V	volume of PSH upper storage
$V_{available}$	available water in reservoir
$V_{demanded}$	volume of water (energy) demanded
$V_{inflow(i)}$	water inflow into the lower reservoir
V_{loss}	total losses outflow volume of water from equivalent reservoir
V_{MAX}	maximum water quantity in upper storage
V_{MIN}	minimum water quantity in upper storage
V_{NAT}	natural water inflow volume
V_{RES}	water volume generated by energy from RES and stored in the upper storage
$V_{supplied}$	volume of water (energy) supplied
V_{TG}	water volume for hydro energy production
V_{TRES}	equivalent reservoir for the needs of TRES
V_{Vis}	volume of the power plant on the island of Vis (Croatia)
W_L	volume of PSH lower reservoir
$X(t)$	energy production in period t
ζ_i	mean productivity of a single reservoir
ζ_{MPI}	pump unit and inverter productivity
η_g	generator efficiency
η_{INV}	inverter efficiency
η_{MPI}	efficiency of motor-pump unit and inverter
η_{PS}	total available efficiency of pump station
η_{RES}	efficiency of a RES
η_t	turbine efficiency
η_{TG}	total available efficiency of turbine and generator
$\xi_{el(HE)}$	productivity of the HE
ρ	density
φ	air humidity

1. Introduction

In view of climate changes due to human activities [1], recent energy policies have been planning bigger share of renewable energy sources (RES) in energy supply. In that sense the policy of EU foresees the share of 20% of RES in total energy production by the year 2020, of which 33.8% is for electric energy [2]. Much more ambitious is the EU policy which, based on the AIP scenario, foresees the share of 50% of RES by the year 2040, of which 82% is for electric energy only [3].

The question is whether these objectives are feasible and based on which technology – concept. The present planning methodology of RES share in energy supply has some serious flaws in technical/technological sense, so the set objectives are not realistically feasible. The main problems of the present concept of development and use of RES are:

(1) Electric power systems (EPS), mostly based on RES, where solar and wind energy prevail, cannot provide continuous energy supply to consumers without energy storage, due to intermittence of input energy. This means that energy from RES with intermittent production (RES-I) is used only when produced.
(2) With the increase of RES share (sun, wind), the need for conventional power plants does not decrease. On the contrary, due to the possibility of production failure from RES-I, it increases along with the need for conventional power plants [4]. Conventional power plants must cover the needs when inputs from RES-I are insufficient.
(3) Systems without energy storage, or very small storage, have greater need for peak power. Namely, considering that conventional EPS practically do not have energy storage, except in the case of hydroelectric storage, electric energy must always be consumed when produced. This also applies to RES. The consequence of this fact is that in EPS generator capacities (power plants) should always cover energy consumption, including peak consumption. This means that significant daily and seasonal power variations in EPS systems caused excessiveness of such systems, in the sense of installed capacities of power plants.

This means that RES-I (solar and wind energy) are for the time being not sufficiently reliable energy sources for EPS, because they cannot provide continuous energy supply. Moreover, the construction of RES will not lead to significant reduction of CO_2 emission from conventional sources as well as water use, nor to the desired effect of climate changes. Therefore, a different approach is necessary in development and use of RES-I, which can realize the vision of sustainable electric power system (SEPS).

This paper analyses the vision of total renewable electricity scenario (TRES), based on innovative strategy of renewable energy sources (RES), called Concept-H. This concept is based solely on the use of renewable resources and predominant use of water storage as energy storage. The prerequisite for realization of TRES is finding the appropriate solution for sustainable electric power system (SEPS) which is presented in this paper. The following describes the basic features as the theoretical foundations of the proposed solution of SEPS which is used to define TRES.

Implementation of SEPS requires a different approach in development of the future EPS than is the case today. All energy sources are in direct connection to EPS, i.e. in unilateral parallel connection, while the connection with pump storage hydroelectric (PSH) is bilateral (Fig. 1(a)).

The approach that enables the realization of SEPS would mostly be based on serial connection concept between energy source and EPS through electric energy storage (EES), as shown in Fig. 1(b).

In this sense the future fully sustainable EPS, i.e. those based solely on RES, would have the configuration as in Fig. 2. Solar (PV and solar thermal) and wind power plants, including other non-continuous energy sources (marine energy) would connect serially/indirectly to EPS through energy storage, while hydro electric, geothermal and biomass power plants would connect directly, because they can provide continuous supply to consumers (RES-C).

In this way electric energy storage (EES) has the key role in realization of SEPS [5]. Numerous technologies of energy storage are known today (batteries, flywheel, pressure vessels, etc.), which differ in size, energy storage costs, efficiency, lifetime, costs per cycle, etc. [6,7]. It is well known that none of the present-day technologies could in terms of ratings be compared to storage by PSH [7,8] (Fig. 3). Precisely because of that, PSH is the most significant EES, which is a mature technology with large volume, long storage period, high efficiency and reliability, while capital cost per unit of energy is low [9].

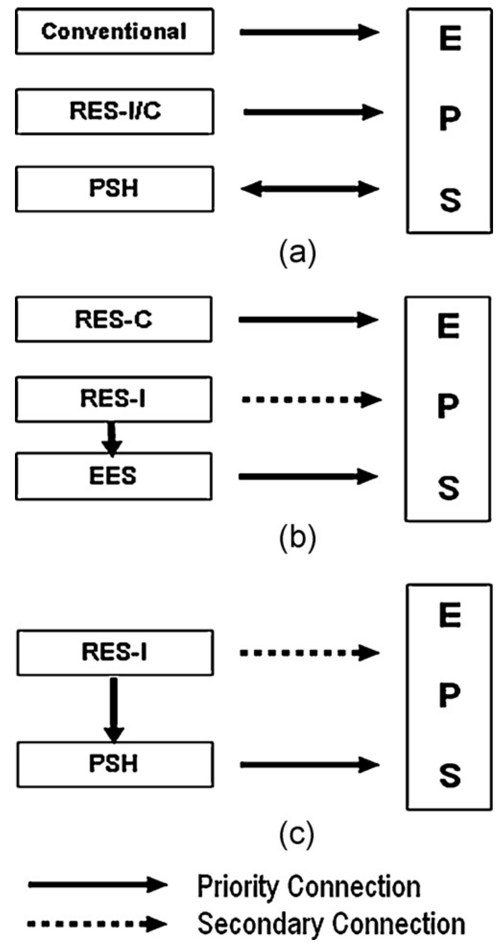

Fig. 1. (a) Conventional connection of energy source and storage; (b) principle concept which would enable SEPS; (c) Concept-H as key element for achieving SEPS.

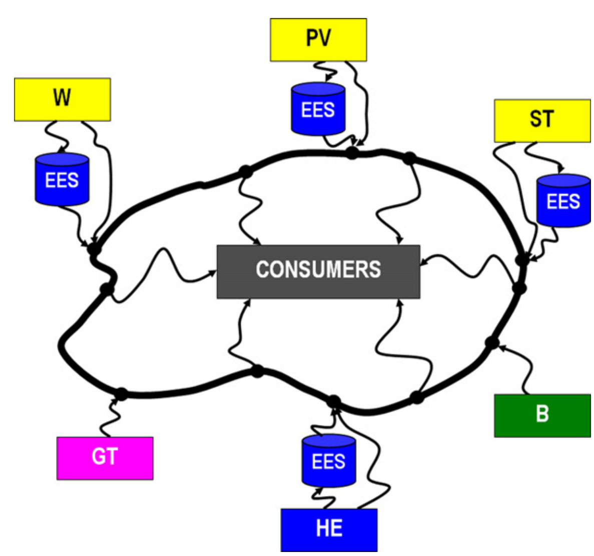

Fig. 2. Vision of the future fully sustainable electric power system (EPS) (PV, photovoltaic; ST, solar thermal; W, wind; GT, geothermal; HE, hydroelectric; B, biomass; EES, electric energy storage).

For this reason, with the present-day technology, SEPS can be achieved only through hybrid system RES–PSH, called Concept-H, whose functional connections are shown in Fig. 1(c). As can be seen, serial connection is the key connection: RES-I, PSH and EPS.

In this concept most energy produced from RES is used for driving the pumps in PSH, i.e. for creating artificial water flow into upper storage of PSH, where water will be stored as hydroenergy potential for energy production. In the same way artificial water inflows into the existing and future hydro electric (HE) power plants could be created, thus increasing their production and operation reliability. The result of this technological concept would be that all energy production would be from renewable sources, without CO_2 emission and water use. In addition, the system does not represent a significant risk to the man and the environment in case of incidental situations, because it is based solely on natural elements and processes.

Conventional drawbacks of the use of PSH [6] are lack of locations for big storages, long lead time, impact on environment, etc. Acceptable locations for big storages are hard to find. However, the construction of smaller storages is not as troublesome as the use of the existing ones. The key objection to operation of storages is that they significantly alter the natural regime of water flow of rivers where they are located. However, PSH do not have such effect, as the same water circulates between lower and upper storage. This means that the hybrid concept can be used in areas with very little water. In addition, PSH can use the sea [10] which has unlimited capacity. This fact is very important, as PSH can be built along the coast, in densely populated areas (65% of the population lives in the coast), therefore in areas with the biggest energy consumers. This means that the new hybrid power plants can be built close to energy consumers, which would significantly reduce energy losses due to transport, which, according to IEC [11] could be between 8% and 15%. It fits easily into the existing energy system and network because energy production is controlled, as in the case of conventional energy sources, i.e. the way PSH and hydro energy are used today for the maintenance of energy system power.

Based on the aforesaid, SEPS is feasible with already available technologies, and with the expected further development of RES technologies it is becoming a promising solution for the sustainable energy system [8].

2. Main settings of the proposed concept

2.1. Main elements of Concept-H

In the green scenario (Fig. 2) continuous renewable energy sources (RES-C) are exploited directly, while marine, wind and solar renewable energy sources (RES-I) are exploited indirectly through PSH.

In the past RES power plants (mostly wind power plants) were combined with HE power plants, supplementing each other, i.e. operating in parallel operation; RES power plant operated when there was sufficient input energy and HE power plant mostly covered peak load [12,13]. The reason for this is economic, because parallel operation causes least energy loss. The new approach foresees serial operation of RES and HE power plants. RES power plants deliver their energy to PSH power plants which then serve for daily and seasonal energy storage, while the consumer is supplied from PSH power plants, transforming intermittent energy supply into continuous energy supply as conventional storage hydro electric power plants [14,15].

Serial connection is based on two pipelines in the classical concept of PSH. This enables continuous independent functioning of pumping station and turbines for energy production, i.e. for energy storage and use of stored energy. One pipeline pumps water from lower water resource into upper storage when RES produces energy and the other conveys water from the upper storage to turbines for production of hydro energy in accordance with the consumer's needs. In this way intermittent operation of RES does not affect hydro energy production according to the consumers' needs.

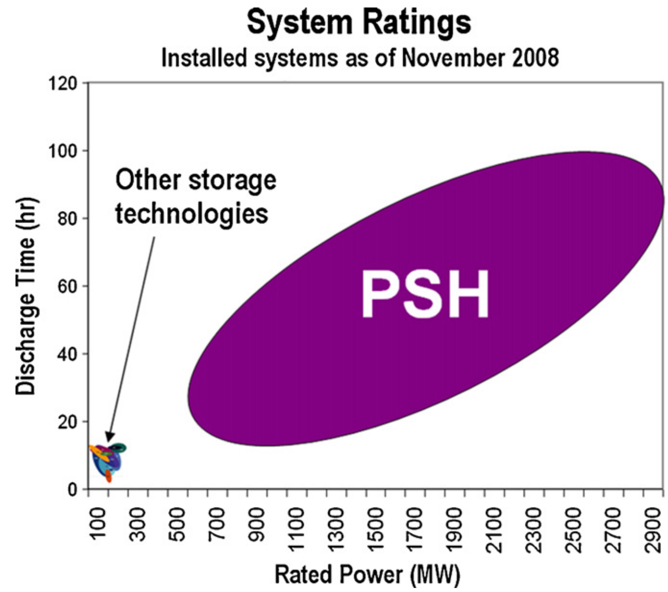

Fig. 3. Storage system ratings in linear scale [8].

The key driving elements of the solution are: (i) RES-I; (ii) energy storage (pump station and storage); (iii) HE. Balancing production and consumption is performed in upper storage based on balance equation of storage volume and HE productivity (Fig. 4).

RES power plants are also in parallel (direct) connection with the regional EPS, because it is logical that RES-I power plant will directly deliver its energy excesses into the system, i.e. when upper storage of PSH is full. It is also logical that energy surpluses in EPS are used for PSH operation. Along with two pipelines in PSH, two energy supply lines from RES power plants are required, one leading to pump station, and the other to EPS. With 2 pipelines within the PSH and 2 energy lines from renewable energy power plant to pump station of PSH and to EPS, Concept-H is the complete.

The solution in the hybrid concept RES–PSH represents a production unit of sustainable energy supply, based on natural resources which is free of charge and constant. It is very flexible in operation and construction and can easily adapt to local conditions, so various combinations are possible, according to natural characteristics of the area, energy system and consumers' energy production needs.

The relation between green energy sources and users, can be expressed as follows:

$$(E_{RES\text{-}I} + E_{RES\text{-}C}) \geq (E_{PSH} + E_{RES\text{-}C}) \geq E_{EPS} \quad (1)$$

where $E_{RES\text{-}C}$ is the energy produced from RES-C, $E_{RES\text{-}I}$ the energy produced from RES-I, E_{PSH} the energy produced from PSH, and E_{EPS} is the energy required for sustainable EPS (SEPS).

Losses occur in energy transfers from one to the other ($E_{RES\text{-}I}$ into E_{PSH}), as well as in transport from the source to EPS. Losses due to energy transfer are inevitable and are the price paid for the new quality in green energy production (Fig. 4). Namely, further efforts should be made in research and development in order to reduce the losses in the production.

Global analysis of this paper causes the use of global equivalent sizes of the solution which is explained below.

2.2. Equivalent power of RES-I power plants

Total energy that the hybrid system of RES–PSH power plant can produce depends on nominal installed power of RES power plant, available RES energy on a certain location and natural water inflows into PSH.

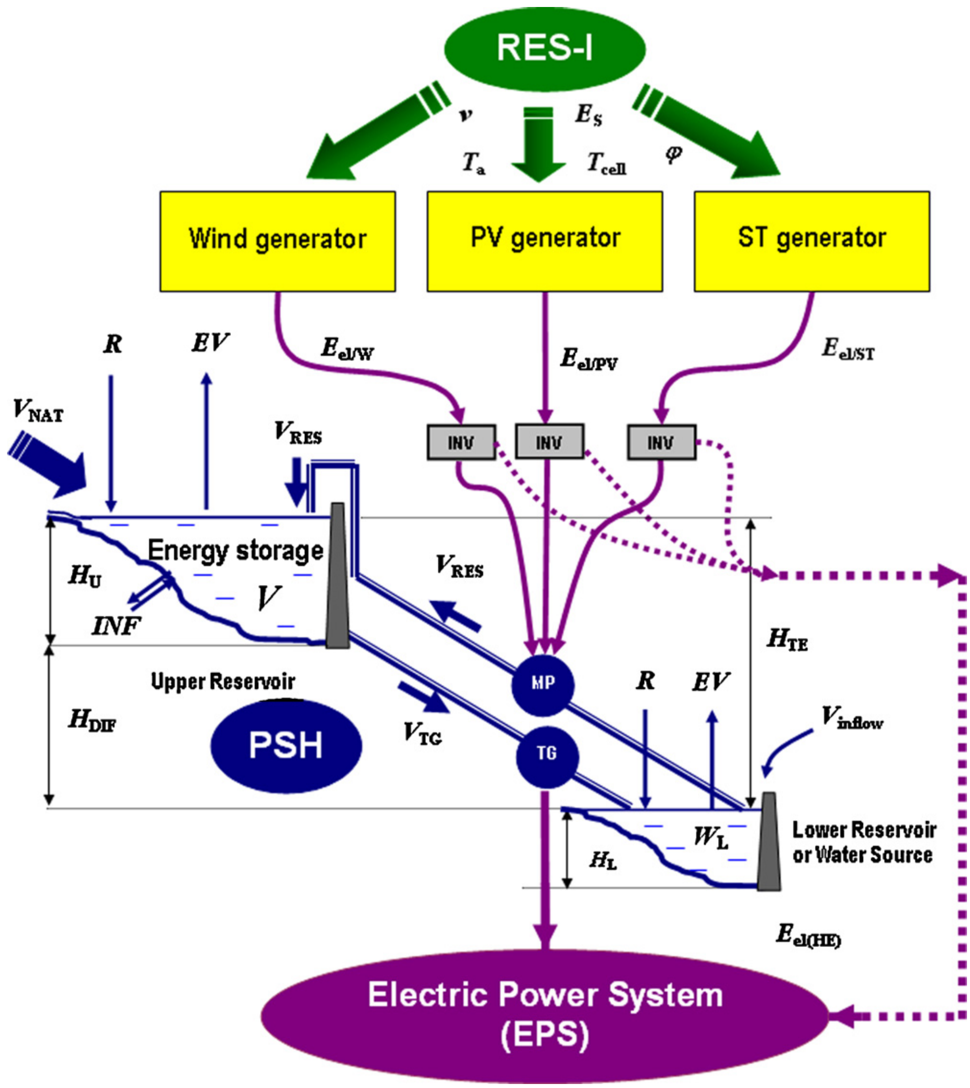

Fig. 4. Concept-H: hybrid power unit as the main building element of the future green systems.

The energy that can be produced in a RES power plant of certain power, can be calculated as annual sum of average daily values of that energy (kWh/(m^2 day)) at some location. However, once the RES power plant and PSH have been sized, total annual energy at a certain location can be calculated more simply from the known capacity factor CF [16] and known nominal power of the RES generator:

$$E_{RES} = P_{el} \times CF \times t \quad (2)$$

where E_{RES} is energy produced by RES power plant, CF is capacity factor of certain RES, P_{el} is power of RES power plant, and t is observation time which is in this case one year.

The CF factor values are listed in literature in different ways. In this paper, for PV [17] and solar thermal (ST) systems with parabolic collectors without energy storage [18], value of 15% will be used, while for wind (W) systems 21% will be used [19]. In the observed PV power plant in the paper of [15] nominal power of 41 MW and CF factor of 0.15, total energy that would be produced by such power plant is: E_{RES} = 41 × 0.15 × 8760 = 53.87 GWh/a, which is very close to the value obtained by precise daily calculation and which is 55,447,234 kWh/a, i.e. about 55.5 GWh/a.

In case in some energy strategies/scenarios energy consumption is already known/estimated, Eq. (2) can give the calculation, sufficiently correct for strategic observation, of the required nominal power of RES power plants (P_{el}) which should cover the energy according to the relation:

$$P_{el} = \frac{E_{RES}}{CF \times t} \quad (3)$$

As has already been said, energy and power from RES power plants are used for operation of pumping stations which generate artificial water inflow into upper storage, and surpluses are delivered to EPS.

2.3. Hydraulic energy of PSH

In the hybrid RES–PSH system water volume stored in the upper storage has been generated by energy from RES (V_{RES}). In case natural water inflows into the PSH system (V_{NAT}), it is added so that total energy of PSH is:

$$E_{PSH(t)} = \rho g H_{TE(t)} V_{TG(t)} \quad (4)$$

where $H_{TE(i)}$ is total head, i.e. average head (difference between upper and lower storage water level increased by hydraulic losses in the PSH pumping system), g (m/s^2) is gravity constant, ρ (kg/m^3) is water density, and t is the time step-period.

$$V_{TG(t)} = V_{NAT(t)} + V_{RES(t)} \quad (5)$$

For the whole year:

$$V_{TG} = \sum_{t=1}^{n} (V_{NAT(t)} + V_{RES(t)}) \tag{6}$$

where n is the number of time steps in the year. If the system is closed, i.e. without significant natural inflows, $V_{NAT(t)} = 0$ and the same water circulates within the system with compensation of smaller losses which are always possible.

Net electric energy $E_{el(HE)}$, produced by the hydro turbines is:

$$E_{el(HE)}\,(\text{J, Ws}) = \rho g H_n V_{TG} \eta_{TG} \tag{7}$$

where H_n is net available drop, and η_{TG} is total available efficiency of turbine and generator (0.75–0.92) [20].

$$\eta_{TG} = \eta_g \eta_t \tag{8}$$

where η_g is the generator efficiency and η_t is the turbine efficiency.

The term $\xi_{el(HE)}$:

$$\xi_{el(HE)} = \rho g H_n \eta_{TG} \tag{9}$$

is also productivity of the HE.

2.4. Equivalent reservoir as energy storage

Global analysis of the capacity required for energy production from PSH power plants uses the method of equivalent reservoir. The equivalent reservoir method is based on the assumption that the volume stored in each reservoir can be converted into potential energy by multiplying it by its mean productivity. In the same way inflows and outflows could be converted into potential energy values. This enables to establish a system energy balance similar to the water continuity equation.

The equivalent reservoir energy balance for a single time step t is expressed as:

$$E_{hyb_t} = E_{hyb_{t-1}} + E_{nat_t} + E_{RES,t} - E_{prod_t} - E_{evap_t} - E_{loss_t} \tag{10}$$

where E_{hyb_t} is the total equivalent reservoir stored energy in time period t (MWh); E_{nat_t} is the total natural potential energy inflow over time period t (MWh); $E_{RES,t}$ is the total energy inflow over time period t (MWh) generated (pumped) by energy from RES; E_{prod_t} is the decision variable or the total energy outflow over time period t (MWh); and E_{evap_t} and E_{loss_t} are the energy outflow corresponding to the losses (evaporated volume and other losses) from the equivalent reservoir over time period t (MWh).

E_{hyb_t} at time t, is the sum (overall potential storage reservoirs in the system) of reservoir-stored volume, multiplied by the accumulated mean productivity taken as its own productivity plus those of the downstream reservoirs, if any:

$$E_{hyb_t} = \sum_{i=1}^{m} \left(V_{i,j} \sum_{j=1}^{k} \xi_j \right) \tag{11}$$

where k is the number of downstream reservoirs from reservoir i (plus itself), and m is the number of reservoirs.

The mean productivity of a single reservoir i (ζ_i) corresponds to the average value over the entire planning horizon.

The evaporation energy losses from the equivalent reservoir (E_{evap_t}) can be defined as:

$$E_{evap_t} = \sum_{i=1}^{m} \text{Surface}_i\, Ev_{i,t} \xi_i \cdot 1000 \tag{12}$$

where Surface$_i$ is the mean surface area of reservoir i (km^2); $Ev_{i,t}$ is the monthly evaporation loss from reservoir i for time period t (mm); and ζ_i is the mean productivity of a single reservoir.

Other losses can be defined:

$$E_{loss_t} = \sum_{i=1}^{m} V_{loss,t} \xi_i \tag{13}$$

V_{loss} is total losses outflow volume of water from equivalent reservoir.

E_{nat} during time period t is the sum of all reservoir natural potential energy inflows (river, rain). For a single reservoir, it is calculated by multiplying the natural water inflow discharge (Q_{nat}) by its mean productivity. Consumptive use water discharges (QC) must be subtracted from the natural inflows. Thus E_{nat} is expressed as:

$$E_{nat_t} = \sum_{i=1}^{m} \xi_i (Q_{nat_{i,t}} - QC_{i,t}) \tag{14}$$

$E_{RES,t}$ during time period t is the sum of all reservoir artificial potential energy inflows (RES). For a single reservoir, it is calculated by multiplying the artificial-RES water inflow discharge (Q_{RES}) by its mean productivity:

$$E_{RES,t} = \sum_{i=1}^{m} \xi_i (Q_{RES,i,t}) \tag{15}$$

$$Q_{RES,t} = \frac{E_{RES}}{CF \times t(\rho g H_{nPS} \eta_{PS} \eta_{INV})} \tag{16}$$

i.e.:

$$Q_{RES,t} = \frac{E_{RES}}{CF \times t \xi_{MPI}} \tag{17}$$

where H_{nPS} is net head of pump station, η_{PS} is total available efficiency of pump station, η_{INV} is efficiency of inverter and ζ_{MPI} is pump unit and inverter productivity.

Only a part of E_{nat} can be converted into electric energy, since during wet periods, reservoirs spill part of the stored energy as the maximum capacity of the power plants is reached. In the case of $E_{RES,t}$, artificial water inflow by means of RES, all energy is consumed, because the inflow into the reservoir is controlled and reservoir spills (energy losses) are rare.

The energy outflow from the equivalent reservoir is the decision variable in the optimization problem, i.e. the desired energy production. The objective function is the mean total electric energy production needed for the particular scenario, i.e. EPS:

$$\max \left[\frac{\sum_{t=1}^{n} (E_{prod_t})}{n} \right] \tag{18}$$

where n is the number of time periods.

2.5. Relation between electric power of the RES generator and storage

Calculation of nominal power P_{el} for pumping water into upper storage and covering the demand for energy in a PSH in time step t is performed according to the characteristics of RES-I power plants (wind, PV and solar thermal). The equation for electric power of a RES-I generator (PV, ST or W) is derived from the equation used for dimensioning of the PV generator, presented in the paper [15] and which can generally be expressed as follows:

$$P_{el(t)} = \frac{2.72 \times 10^{-3} p_{RES} H_{TE(t)}}{\eta_{RES(t)}(T_a, \upsilon, \rho, \varphi) \eta_{MPI} E_{RES(t)}} V_{RES(t)} \tag{19}$$

where p_{RES} (W/m^2) is equivalent value of RES-I power reference value (for solar systems it is 1000 W/m^2); η_{MPI} is efficiency of motor-pump unit and inverter; $\eta_{RES}(T_a, \upsilon, \rho, \varphi)$ is exploitation efficiency of a RES, which depends on air temperature T_a, density ρ,

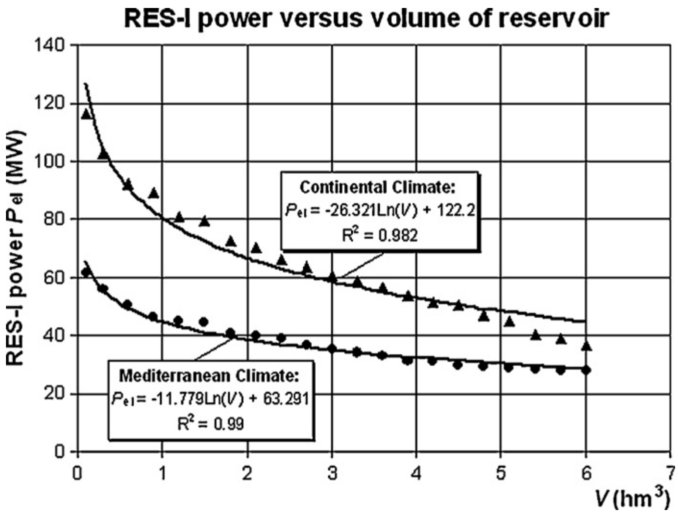

Fig. 5. Relation between P_{el} of RES-I power plant and reservoir volume V and the required P_{el} depending on power supply reserve for the areas with Mediterranean and Continental climate.

wind velocity v and air humidity φ; $H_{TE(t)}$ (m) is total head; $V_{RES(t)}$ (m^3) is total water volume to be pumped by RES-I power plant into upper storage in order to satisfy daily energy consumption; E_{RES} (kWh/m^2/day) is average daily energy from RES-I, available for energy production.

Eq. (19) applies for one day which can then be used as the basic time discretization unit t for the planned analysis period.

In that period it is required to find the electric power which will in the best way possible satisfy the needs of a consumer. Therefore, a systematic approach to the problem is required, connecting all relevant values in the system, upon which by Eq. (19) optimal P^*_{el} could be calculated in the similar way as is shown in the paper Glasnovic and Margeta [15].

Apart from E_{RES} and the size of the consumer, expressed in Eq. (19) by $V_{RES(t)}$, it can be seen that upper storage volume V also has a dominant effect on P_{el}. Due to this, it has been separately analysed and presented in Fig. 5. As can be seen, by increasing the size of the upper storage, P_{el} of RES power plant decreases by logarithm function:

$$P_{el} = -a\,Ln(V) + b \tag{20}$$

where P_{el} is the power of RES-I (W), V the operational volume storage (m^3). and a and b are parameters based on location characteristic and technological features.

However, these relations between P_{el} and V of the reservoir mean less investment required for installed capacities of RES power plant, providing sufficient space is secured for water storage:

$$V_{MIN} \geq \frac{E_{prod_{MAX,t}}}{\xi} \tag{21}$$

$$V_{MAX} \leq V_{available} \tag{22}$$

P_{el} and V are optimized according to characteristics of the problem.

The relation between P_{el} and V can also be observed through the required power supply reserve in the system. If the reserve decreases it is logical that the required power of RES power plant will increase and vice versa, all in order to achieve the desired reliability of energy supply.

The reliability of the system by volume R_V or energy R_E is equivalent to performance index; it relates the volume of water (energy) supplied ($V_{supplied}$) and to the volume of water (energy) demanded ($V_{demanded}$) for the analysis period:

$$R_V = \frac{V_{supplied}}{V_{demanded}} \tag{23}$$

Therefore, it can be concluded that Concept-H can be applied in a wide range of climate conditions [21], whereat the required capacities of RES power plant and reservoir, i.e. their relation and total investment required, will depend on local conditions and availability of RES-I, i.e. on the possibility of constructing the reservoir at a certain location. This requires good planning and optimal sizing of Concept-H, according to characteristics of the area and needs.

2.6. Equivalent reduction of CO_2 emission

Based on the data contained in IEA [22], it can be seen that in 2007, 8228 TWh of electric energy production was from coal (41.5%), 1114 TWh (5.6%) from oil and 4127 TWh (20.9%) from natural gas, i.e. that 68% of total world electric energy production (13,469 TWh) was from these "unclean" fuels. It is also possible to calculate how much CO_2 could be saved if the same trend of energy production from non-conventional energy sources were to continue.

By taking into account that coal power plants emit 0.955 kg CO_2/kWh, oil driven power plant emit 0.893 kg CO_2/kWh and gas power plants 0.599 kg CO_2/kWh [23,24], by replacing the power plants with conventional fuels that emit relatively large quantities of CO_2 into the environment, it is possible to calculate the equivalent value of CO_2 emission ($M_{CO_2(Eq)}$) as weighed moving average value by equation:

$$M_{CO_2(Eq)} = \frac{\sum_{f=1}^{N} M_{CO_2(f)} E_{NRES(f)}}{\sum_{k=1}^{N} E_{NRES(k)}} \tag{24}$$

where $M_{CO_2(f)}$ is unit emission of each fuel that emits CO_2 (coal, oil and natural gas), $E_{NRES(k)}$ is the energy of each fuel and f is the type of fuel assuming values up to N. In this concrete case weighed moving average is:

$$M_{CO_2(Eq)} = \frac{61 \times 0.955 + 8.2 \times 0.893 + 30.7 \times 0.599}{61 + 8.2 + 30.7} = 0.84\,\text{kg}\,CO_2/\text{kWh}.$$

3. TRES scenario

3.1. EREC forecast and its upgrading by RES + PSH systems

The electric energy consumption according to AIP Scenario of EREC forecast [3] is shown in Table 1. As can be seen, the scenario foresees the use of: biomass (B) 4290 TWh, large hydro (LHE) 4165 TWh, small hydro (smHE) 2200 TWh, wind (W) 8000 TWh, PV 9113 TWh, solar thermal (ST) 790 TWh, geothermal (GT) 1020 TWh and marine (M) 230 TWh. 18% of the required energy is intended for covering from non-renewable RES (i.e. NRES). Therefore, for the year 2040 such EREC scenario can be expressed by the following relation:

$$\text{TOTAL} = 12\%\text{B} + 11\%\text{LHE} + 6\%\text{smHE} + 22\%\text{W} + 25\%\text{PV} + 2\%\text{ST} + 3\%\text{GT} + 1\%\text{M} + 18\%\text{NRES} \tag{25}$$

where TOTAL shows total production (consumption) of energy, or more simply:

$$\text{TOTAL} = 82\%\text{RES} + 18\%\text{NRES} \tag{26}$$

Table 1
AIP scenario, share of renewables in world total electricity consumption [3].

		Year				
		2001	2010	2020	2030	2040
	Total consumption in TWh (IEA)	15,570	19,973	25,818	30,855	36,346
1	Biomass (B)	180	390	1010	2180	4290
2	Large hydro (LHE)	2590	3095	3590	3965	4165
3	Small hydro (smHE)	110	220	570	1230	2200
4	Wind (W)	54.5	512	3093	6307	8000
5	PV	2.2	20	276	2570	9113
6	Solar thermal (ST)	1	5	40	195	790
7	Geothermal (GT)	50	134	318	625	1020
8	Marine (M)	0.5	1	4	37	230
9	Total RES	2988.2	4377	8901	17,109	29,808
10	RES contribution (%)	19	22	34	55	82
11	(PV + W + ST) + PSH	58	537	3409	9072	17,903
12	(PV + ST + W) + PSH contribution (%)	0	3	13	29	49
	NRES	12,582	15,596	16,917	13,746	6538

However, as has been said in Section 1 of the paper, this EREC forecast is not easily feasible with such share of RES without adequate energy storage.

In order to solve the resulting problem, the EREC strategy should be upgraded by using hybrid systems of PV + PSH, W + PSH and ST + PSH power plants instead of PV, W and ST systems/power plants.

Therefore, in the EREC energy balance, apart from the more significant RES, adequate electric energy storage should be planned, in the form of PSH system. This can be shown by the equation:

$$\begin{aligned}\text{TOTAL} = {} & [(25\%\text{PV} + 22\%\text{W} + 2\%\text{ST}) + \text{PSH}] + (12\%\text{B} + 11\%\text{LHE} \\ & + 6\%\text{smHE} + 3\%\text{GT} + 1\%\text{M}) + 18\%\text{NRES} \end{aligned} \tag{27}$$

If the more significant RES (sun and wind) were expressed only as RES and the other RES as ORES, Eq. (27) could be simpler:

$$\text{TOTAL} = 49\%(\text{RES} + \text{PSH}) + 33\%\text{ORES} + 18\%\text{NRES} \tag{28}$$

Therefore, 49% of RES systems would have energy storage, which would provide significant reserve. Such EPS could provide their consumers with the necessary electric power, i.e. they would guarantee high reliability of supply.

3.2. Total renewable electricity scenario (TRES)

Although the EREC forecast [3], supported by hybrid RES–PSH systems, significantly increases the share of RES in the future EPS, 18% of NRES still remains, which would continue to emit CO_2 to the environment. As Concept-H has been introduced in this paper, conditions have been created for covering those 18% from the more significant RES, i.e. sun and wind.

As it is difficult to estimate which direction the development of RES technologies will take until the year 2040, this paper has retained the relation which PV, ST and W technologies have in EREC scenario. This means that the 18% of NRES would be distributed proportionally with the share of each RES, i.e. additional 9% would relate to PV systems, additional 8% to W systems, and additional 1% to ST systems. This means a total of 34% for PV systems (12,358 TWh), 30% for W systems (10,904 TWh) and 3% for ST systems (1090 TWh). In that case Eq. (27) would be:

$$\begin{aligned}\text{TOTAL} = {} & [(34\%\text{PV} + 30\%\text{W} + 3\%\text{ST}) + \text{PSH}] + (12\%\text{B} + 11\%\text{LHE} \\ & + 6\%\text{smHE} + 3\%\text{GT} + 1\%\text{M}) \end{aligned} \tag{29}$$

and Eq. (29) would become:

$$\text{TOTAL} = 67\%(\text{PV} + \text{W} + \text{ST} + \text{PSH}) + 33\%\text{ORES} \tag{30}$$

Eq. (30) shows that the future TRES could have 67% of the share of the more significant RES-I (sun and wind), while the entire quantity of RES-I would be covered/supported by energy from the corresponding PSH systems. This would mean significant reserve in the future EPS which would ensure their high reliability of electric energy, but also power supply.

3.3. System development

Obviously, the objective values of energy production from RES cannot be achieved before the year 2040. Therefore, it would be better to plan that this development and increase of all RES follow the S-curve. However, the authors of this paper have retained all growth trends of RES share as in the EREC forecast, except for PV, W and ST, which would be combined with PSH systems for which this paper foresees energy production $X(t)$ following the S-curve:

$$X(t) = a(1 - e^{-b(t-c)^d}) \tag{31}$$

where a, b, c and d are constants derived from the curve.

S-curve is used because the period in question is very long and the lifetime of some RES systems, which will be installed first, will gradually expire (about 25 years for W systems [25] and 28 years for PV systems [26]), therefore it is logical that, with the approaching of the year 2040, the increasing trend of installed RES systems will decrease. Also, as is always the case with new things, it will take time to accept all this and to prepare new development and production plans, etc. Therefore the intensity of changes will be smaller at first, then stable and finally descending, asymptotical, nearing the strategic sustainability objective.

In the concrete case the same values of RES share based on EREC forecast for the years 2001 and 2010 have been retained (because those years cannot be influenced any more); in the objective year 2040 the share of various RES + PSH technologies is foreseen based on Eq. (29); the share of RES–PSH technologies for the years 2020 and 2030 is calculated by Eq. (31); ORES as well as all other RES technologies remain exactly the same as in EREC forecast. Thus the new world total renewable electricity scenario (TRES) is developed, presented in Table 2 and in Fig. 6.

Therefore, based on this scenario, the development of RES + PSH systems is foreseen until 2010 and such developed EPS systems would be very reliable, because 67% of total energy production

Table 2
Development of world total renewable electricity scenario.

		Year				
		2001	2010	2020	2030	2040
	Total consumption in TWh (IEA)	15,570	19,973	25,818	30,855	36,346
1	Biomass (B)	180	390	1010	2180	4290
2	Large hydro (LHE)	2590	3095	3590	3965	4165
3	Small hydro (smHE)	110	220	570	1230	2200
4	Wind (W)	2	20	6179	10,885	12,447
5	PV	55	512	5452	9604	10,904
6	Solar thermal (ST)	1	5	545	960	1090
7	Geothermal (GT)	50	134	318	625	1020
8	Marine (M)	0,5	1	4	37	230
9	Total RES	2988	4377	17,668	29,486	36,346
10	RES contribution (%)	19	22	68	96	100
11	(PV + W + ST) + PSH	58	537	12,176	21,449	24,441
12	(PV + ST + W) + PSH contribution (%)	0	3	47	70	67

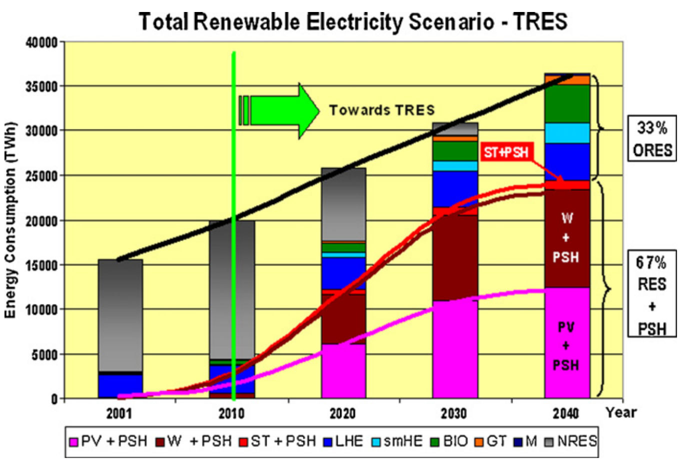

Fig. 6. Development of world total renewable electricity scenario until 2040 (S-curves denote development of (PV + ST + W) + PSH systems).

would be provided by PV + W + ST units with energy storage in the form of PSH system.

3.4. Estimate of the required size of RES and PSH

Table 3 shows what in this case the transition to TRES, i.e. implementation of RES–PSH systems means. The table refers to the objective year 2040, where for all three hybrid technologies PV–PSH, W–PSH and ST–PSH, column (1) contains energy consumption production; column (2) contains capacity factors; column (3) shows total required power of RES technologies; column (4) shows unit area taken up by a certain RES technology; column (5) shows total area that will be taken up by a certain RES technology; column (6) shows the PSH volume; column (7) shows energy stored in PSH; and column (8) contains saving of CO_2. The results refer to the strategy which maximally prefers RES energy sources over the required volume of the reservoir (min equivalent storage volume).

As the data for one analysed hybrid power plant are known [15], the same was used to establish the equivalent reservoir for the needs of TRES:

$$V_{TRES} = \sum V_{Vis}; \quad \text{i.e.}\ E_{TRES} = \sum (V_{Vis} p_{Vis}) \tag{32}$$

where V_{Vis} is the volume of the power plant on the island of Vis (Croatia) and p_{Vis} is hydro electric power plant productivity.

Total power (TW) of RES generator is calculated by Eq. (3); unit areas (km^2/TWh) have been obtained from WEC [27]; total area is obtained from columns (1) and (3); PSH volume is obtained by Eq. (32) (equivalent value of reservoir volume for the island Vis, Croatia); PSH energy is obtained from Eq. (4); and CO_2 saving from Eq. (24).

The total power of all RES-I power plants would amount to about 16 TW. For land use the reduction of W and ST power plants, in relation to the present-day values, was not calculated, although it is logical that it will happen in the oncoming period of 30 years, especially for the ST power plants. However, for the PV power plant it is logical to calculate this reduction because a very large increase in efficiency (multijunction cells) is expected in this area, which, according to Green [28], could be up to 58%. In that case, for all PV systems unit value of about 0.89 km^2/TWh can be taken. Adding up the present values of land use for the W and ST power plants and the estimated values for the PV power plants, the total area of RES-I system of about 29,517 km^2 is obtained, which is far below the technical potential of RES systems, which according to de Vries et al. [29], for PV and W systems is 4166 PWh. This means that in the roughest terms, the total area obtained in this way is 0.5% of technical potential.

The total required equivalent reservoir volume of 880 km^3 is a value that amounts only to about 8% of all artificial reservoirs constructed in the world to the day, which is 10,800 km^3 [30].

Table 3
Estimate of typical values of the applied Concept H in the year 2040.

	RES + PSH (67% of TRES)	1	2	3	4	5	6	7	8
		Total electricity consumption (TWh)	CF (%)	Total power (TW)	Unit area (km^2/TWh)	Total area (km^2)	PSH volume (km^3)	PSH energy (TWh)	CO_2 saving (Mt)
1	PV + PSH	12,447	16	8.9	0.9	11,078	448	261	10,461
2	W + PSH	10,904	21	5.9	1.3	14,557	393	229	9164
3	ST + PSH	1090	16	0.8	3.6	3883	39	23	916
	TOTAL	24,441	–	16	–	29,517	880	513	20,542

Based on the power of PSH of Vis, the power of equivalent reservoir of PSH, can be estimated at about 5.9 TW.

As has been said, the key element of reliability of energy production from the more significant RES is hydro accumulation that can store energy of 513 TWh, which is an additional reserve for about 10 days of system operation in 2040.

As can be seen, CO_2 emission saving would be significant and could be 20,542 Mt CO_2, i.e. about 20 Gt CO_2.

However, based on analysis in Chapter 2.4, the size of RES power plants will also depend on the size of associated reservoirs, meaning that bigger reservoirs will in the first place result in higher security of energy supply and will require smaller installed capacities of RES power plants (Eq. (20)).

Specifically, if this increase of reservoir volume was about three times bigger than the obtained 880 km^3, it would significantly increase reserves in the system (about a month), while the power of all RES-I power plants (equivalent power PV + W + ST) of 16 TW, could decrease to about 10 TW, and thereby significantly reduce the land use and investment in these systems. It is obvious that the proposed solution enables the development of different scenarios according to the particularities of individual countries.

3.5. *Economic and financial characteristics*

Without regard to the necessity of achieving TRES, it is logical to question the economic characteristics of the proposed solution and possibilities of its financing. In this sense, it is well known that the RES are built and that more extensive construction is planned. Therefore, the possible development of TRES basically does not have specific economic characteristics in relation to current trends and building costs. However, by gradual implementation of TRES and thus increase of the use of green energy, and because of mass production, reduction of prices of various products is expected. An increase in their effectiveness is also to be expected, especially for PV generators, and thereby the reduction of energy production costs (according to Green [28] the prices could even fall to a value of 0.2 $/W$_p$ and thus significantly reduce investment in RES systems). This means that the possible strategy in order to achieve TRES, actually creates a framework for better economics for implementation of RES and green energy production.

On the other hand, the increase of importance of RES in the energy system, as well as their use by consumers, depends on the development of energy storage. PSH is one of the simpler and less expensive storage solutions, especially in case of larger capacity. This is currently the cheapest solution, so that the proposed concept for the realization of TRES is more cost effective than other known technologies.

It is known that the energy produced from RES is subsidized so that investment is cost effective for the investors and acceptable to the EPS. The energy produced by the proposed concept is undoubtedly better for EPS because it can be managed so that subsidizing this energy is more acceptable than energy from RES, which is less manageable and has a higher production variability and uncertainty. As it reduces the need for the development and use of conventional energy sources (in this sense, it is logical that the funds that are now allocated to conventional fuels be redirected to the construction of new RES power plants), it is obvious that it is also more economical than the current concept of using RES in EPS.

So, if TRES and production of green energy are to be accomplished, the proposed solution, even without detailed analysis is more cost-effective than the current solutions and concepts. Precise evaluation of such investments is difficult to make without more detailed and comprehensive analysis beyond the scope of this paper.

However, based on the current costs for W, ST and PSH, as well as the cost of PV systems, it is possible to obtain approximative investment costs for the period 2020–2030:

- In the paper of Deane et al. [9], current investment costs in PSH are estimated at 0.434 $/W, which will be retained in this estimate for the period 2020–2030, although they will continue to decrease, specially with the increasing number of reservoirs.
- In the paper of Nej [31] and Keshner and Arya [32], 2004, investment costs in PV systems for the period 2020–2030 can be estimated at about 1 $/Wp.
- In the paper of Nej [31] investment costs in W systems for onshore wind turbines are estimated at 0.7–1.0 €/W in 2006, which will decrease until the period 2020–2030. However, for this rough analysis, average investment cost for W systems of about 1 $/W can be taken for the period 2020–2030.
- In the paper of Williges et al. [33], investment cost in solar thermal power plants with parabolic collectors are estimated at 803 €/kW in 2030, which is also very close to the cost of about 1 $/W.

Therefore, in a very rough approximation for the period 2020–2030, an equivalent price of RES-I system of about 1 $/W can be used, and 0.434 $/W for PSH systems.

Based on the prices stated, a very rough investment estimate in RES-I systems could be:

(a) For RES power plants 16 TW × 1 $/W = $16 trillion.
(b) For PSH power plants 5.9 TW × 0.434 $/W = $2.56 trillion.

This means that total investment in TRES could be estimated at about 18.5 trillion $, which, for the period of 30 years means 0.61 trillion per year.

Since, according to the International Monetary Fund [34], the world GDP was 57,937.460 billion dollars in 2009, i.e. about 58 trillion dollars, we can see that investment of $0.61 trillion mainly comes down to the value of about 1% of the world in 2009. Naturally, the world GDP will increase in time (some estimates show that in the 2040 it will be around $80 trillion [35]), which means that investment value in TRES could be well below the calculated 1% of GDP in 2009. Therefore, based on these very rough estimates, we can see that TRES is also feasible from financial point of view.

4. Comments and conclusions

This paper points to the possibility of realization of TRES, as well as EREC scenario, by a different concept, the so-called Concept-H. It is a technological concept of hybrid RES–PSH systems which provides continuous energy production, the same as conventional energy sources.

The accent is on hydroenergy, i.e. PSH as the main building unit, because this concept is flexible in implementation and provides continuous supply of “green” energy and can be built in a wide range of climate areas, locations and water resources [21]. The proposed production unit usually has very small impacts on the environment because it causes minimal changes in local and global hydrology and eco systems, and has a low level of potential danger for people and environment in case of incidental situations. As transition to this system is a long-term process (30 and more years) and as further development of RES technologies will take place, it is realistic to expect that construction of new RES–PSH units will be easier.

Another advantage is that TRES could be planned systematically and extensively, i.e. new RES + PSH units could be constructed extensively, as close as possible to the consumers, which would evade high costs of transportation and distribution of energy, contributing to realization of a relatively better operating plan. Extensive construction has less impact on the environment and

provides greater local security in case of problems in transport, as well as overall vulnerability of EPS. Naturally, such sustainable system would have to be optimized, which would lead to full energy independence of certain locations and settlements.

The paper observes equivalent sizes of RES–PSH systems and in this regard it has been determined that the required/equivalent power of RES system in 2040, which would satisfy the overall energy consumption of 24,441 TWh/a of energy, could amount to around 16 TW, and the equivalent reservoir volume of 880 km^3. The realization of such power of RES-I system would require the area (land use) of 29,517 km^2 or a total of only about 0.5% of the technical potential of RES exploitation, while the total volume of the equivalent reservoir of PSH would be only about 8% of the total volume of artificial reservoirs constructed to the day (10,800 km^3). Both, the required surfaces of RES and volumes of artificial reservoirs clearly show that, in terms of necessary physical capacities, TRES is realistically feasible.

In such TRES total energy reserves would amount to 513 TWh, which is enough for operation of the whole system for ten days, with no other energy input into the system. The global hydroenergy policy is shown by an equivalent tank that replaces all the possible reservoirs that potentially could be built. By solving energy reserves in the system, the problem of providing the necessary power to consumers is solved, which is the key difference in relation to all previous energy scenarios that provided the consumers with sufficient energy in annual balances, but not the necessary power. Precisely this fact allows achieving a system that is entirely based on RES, which for the first time clearly shows that the TRES is realistically feasible.

Naturally, the reserves in the system can also increase, whereat the paper in an original way sets up the relationship between the equivalent power of RES and equivalent reservoir volume. Larger volume will also mean greater reserve in the system, and this will result in less required power of RES. The selected reserve, i.e. the relation of increase in equivalent reservoir volume and the required power of RES depends on a number of parameters (local climate, terrain configuration, etc.) and it is the matter of optimization and evaluation of whether it is more cost effective to invest in PSH systems or RES-I power plants at a certain location.

The disadvantages of TRES with big participation of RES generator lie in the first place in their price, which is today 3, or 4–5 times bigger than the price of conventional power plants of equal rating. However, regardless of the high production costs, RES are being built and more will be built as a necessary precondition for achieving the desired sustainability. That is why today their energy production is subsidized. If this is so, then there is no reason not to build RES sources which, combined with PSH, are by energy production features, equal to conventional sources. However, this increase in production of RES technologies will logically lead to the reduction and their prices. In this sense, estimates from this paper suggest that investment in RES–PSH systems could be about 1% of the world GDP in 2009, and they all point to the fact that the TRES is realistically feasible from the financial point of view.

It is possible to ask the question why the problem of intermittence of RES power is not solved by regional dispersion and interconnection, which can smooth total output. The reason for this lies in the fact that although these measures can significantly improve the security of supply of consumers and reduce the required reservoir volume, they cannot at any time guarantee to the consumers a certain electrical power. Specifically, in a system with RES-I, without proper storage of energy, it is very difficult to avoid the situation that power consumption in a given area (no matter how big it is), is greater than production. Thus, these EPS would not be reliable enough. This results in another problem, for example, a wind power plant on one location would have to replace the wind power plant energy on another location where there is not enough wind. It also means that the installed capacity of these wind power plants would have to be much larger, rather than simply storing the energy that they produce. In addition, another significant problem would arise, it would increase the occurrence of losses in the transmission lines.

In the realization of TRES, problems related to unequal development of individual countries, the speed of their economic development and the unequal availability of RES-I system could arise. However, problems can arise due to different economic interests of certain countries regarding other technologies, and possibly a lack of political will for joint activities in this area.

Although from the point of view of other energy sources, this paper may seem like an extreme case, it basically just gives a different vision of development of the power system, based on EREC AIP scenario [3]. When considering different options, it is very important to properly evaluate the technologies that are planned to be applied in relation to their impact on the environment (the impact of nuclear technology on the environment, such as in the paper of Verbruggen [36]), but also the needed additional financial incentives (as is specified for CCS technology in Tzimas and Georgakaki [37]). Precisely due to undisputable advantages of Concept-H, which has enabled sustainable (or green) energy supply, in this paper it is taken as a basic building unit of the future TRES, and the orientation towards TRES would open another choice of solutions to decision makers. An increasing number of papers that consider 100% of RES support this orientation [8,38–41].

Although we consider the energy efficiency measures very important, the development of TRES is currently the most important step, because desirable results could be quickly obtained (slowing of environment degradation). This policy is in accordance with the newest tendency in that area [42,43].

The paper analyses the effect of transition to TRES, i.e. implementation of RES–PSH systems from the initial 2010 to the objective 2040. As has been shown, total energy of 24,441 TWh/a in 2040 would party be covered from PV + PSH systems (12,447 TWh/a), partly from W–PSH systems (10,904 TWh/a) and to a smaller extent from ST–PSH systems (1090 TWh/a), which would be 67% of total energy consumption (these studies retained the same share trends of certain types of RES as in EREC forecast [3], although new, very ambitious plans of constructing big solar systems and wind power plants in the North of Africa, should be borne in mind, EUMENA [44,45] which could significantly change these relations). However, it should also be borne in mind that simultaneously with the construction of major ST systems, big PSH systems should also be planned to ensure the required reliability of the system.

Nevertheless, the most important is very big saving on CO_2 emission that would result from application of Concept-H and which could be up to 20 Gt CO_2 per year. In addition, this solution does not consume water that is a vital and increasingly limited resource for the man, which is also of importance for achieving sustainability. It also does not present potential significant risk to people in case of incidental situations, because it is based exclusively on renewable energy and natural processes.

It is known that decision-makers, as well as international institutions give increasing emphasis to renewable energy sources (RES) in energy supply as one of the elements of the strategy for achieving sustainability. This means that the long-term achievement of TRES is desirable. In this paper, the idea is discussed and it was determined that the proposed solution can probably be realized. Therefore, the proposed solution should be considered as an additional strategy to current strategies in finding solutions to the production of green energy.

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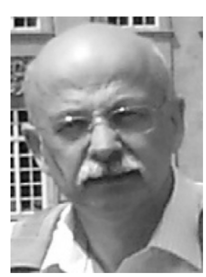

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